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We have carried out fully self-consistent simulations of FEL dynamics in strongly tapered amplifiers. These are one-dimensional initial-value studies in which the electrons obey the single particle Hamiltonian equations that include the magnetic field of the wiggler as well as the space and time-dependent radiation field. The radiation field obeys Maxwell's equation (in the paraxial approximation), with the source current calculated self-sonsistently by summing over the electrons. The results of this simulation for the strong linear taper confirs the predictions of our earlier analytical theory on strong sideband suppression.

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Final Report on Grant No. F49620-96-1-0068 (1996-99) with the Air Force Office of Scientific Research

TITLE: EFFICIENCY ENHANCEMENT, SIDEBAND SUPPRESSION, AND OPTICAL PULSE GENERATION IN STRONGLY TAPERED FREE-ELECTRON LASERS

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WORK COMPLETED

The work completed during this grant period has been published in refereed journals and is attached to this Report. Below we give a brief summary. For details, the reader is referred to the attached publications.

Efficiency Enhancement and Sideband Suppression in Strongly Tapered Free Electron Laser Amplifiers

We have carried out fully self-consistent simulations of FEL dynamics in strongly tapered amplifiers. These are one-dimensional initial-value studies in which the electrons obey the single-particle Hamiltonian equations that include the magnetic field of the wiggler as well as the space and time-dependent radiation field. The radiation field obeys Maxwell's equation (in the paraxial approximation), with the source current calculated self-consistently by summing over the electrons. The results of this simulation for a strong linear taper confirm the predictions of our earlier analytical theory [R. P. Pilla and A. Bhattacharjee, Phys. Plasmas 1, 390 (1994)] on strong sideband suppression. It is found that strong quadratic tapers are optimal because they yield relatively compact wiggler configurations (~8m long). For short-wavelength (~10 microns) FEL amplifiers with a quadratic taper, sideband intensities are depressed nearly six orders of magnitude relative to that of the primary signal, and efficiencies in the range of (33-50)% are obtained under realistic beam conditions.

The theory has been extended to include the effect of diffraction, which makes the problem inherently two-dimensional. It is demonstrated numerically that strong tapering of the wiggler can suppress the growth of sidebands in regions of weak as well as strong diffraction, thus extending the validity of the earlier two-dimensional results.

The primary significance of the effort described above is the possibility of producing tunable high-power radiation that is spectrally pure (i.e., devoid of parasitic sideband frequencies) at high efficiencies (33-50%) from a relatively compact FEL amplifier. To the best of our knowledge, our conceptual design have achieved this optical purity with an unprecedented efficiency of energy conversion. Such tunable high-power radiation sources have many applications, both civilian and military.

Ginzburg-Landau model for free-electron laser amplifiers and oscillators

There is experimental evidence, first reported by the group at the University of California at Santa Barbara (UCSB), that a long-pulse FEL tends to operate on a very narrow bandwidth, and possibly in a single mode. We have developed a new theoretical model, based on the Ginzburg-Landau equation, to elucidate the conditions under which single-mode operation of a FEL can be attained, and resolve the differences between the two theoretical approaches. Our theoretical formulation has been applied to amplifier as well as oscillator configurations.

We show that the nonlinear dynamics of the radiation field (A) in the presence of multiple modes obeys the Ginzburg-Landau equation

$$\frac{\partial A}{\partial z} = i\lambda_0 A - \frac{1}{v_g}\frac{\partial A}{\partial t} - \frac{i\alpha}{2}\frac{\partial^2 A}{\partial t^2} + i\beta|A|^2 A \ ,$$

where $\lambda_0(\omega)$ is the growth rate, $v_g \equiv c/(1 + c\partial\lambda_0/\partial\omega)$ is the group velocity, and $\alpha \equiv \partial^2\lambda_0/\partial\omega^2$ and β are complex parameters calculated by the theory. This Ginzburg-Landau equation has been extensively considered in the mathematical literature on nonlinear waves, and two types of instabilities have been identified: the Benjamin-Feir and the Eckhaus instability. In a Benjamin-Feir instability, every mode is unstable, and therefore, it is not possible to obtain single-mode operation. In an Eckhaus instability, a single mode solution is stable if its frequency lies in a certain range, but becomes unstable outside of this range.

We show, rather remarkably, that for long-pulse FELs there is no Benjamin-Weir instability, and that the main mode with the largest gain is always stable. However, a Eckhaus instability can occur, and can lead to two distinct possibilities. One possibility, realized in the UCSB experiment, is that there is spontaneous frequency-shifting to the stable mode with the largest growth rate, with a consequent tendency to approach single-mode operation asymptotically. The other possible regime for the Eckhaus instability is to produce a chaotic radiation field. It is suggested that "optical spikes", seen in several experiments, can be interpreted as the transient manifestation of the second type of Eckhaus dynamics. The probability of realizing a single mode starting with random initial conditions is calculated and compared with spectral measurements from the UCSB FEL.

PERSONNEL SUPPORTED
Faculty : A. Bhattacharjee, Professor of Physics and Astronomy
Post-Doctoral Fellow: C. S. Ng

PUBLICATIONS

Sideband suppression and efficiency enhancement in a strongly tapered free-electron laser amplifier, J. Chen and A. Bhattacharjee, Nuclear Instruments and Methods in Physics Research **A 375**, 363 (1996).

Free-electron lasers, A. Bhattacharjee, in the *McGraw-Hill Yearbook of Science and Technology 1997* (McGraw-Hill, New York), pp. 267-269.

Ginzburg-Landau model for mode competition and single-mode operation of a free-electron laser, C. S. Ng and A. Bhattacharjee, Physical Review E **58**, 3826 (1998).

Ginzburg-Landau model of a free-electron laser: from single mode to spikes, C. S. Ng and A. Bhattacharjee, Nuclear Instruments and Methods in Physics Research A **407**, 34 (1998).

Ginzburg-Landau model for a long-pulse low-gain free-electron laser oscillator, C. S. Ng and A. Bhattacharjee, Nuclear Instruments and Methods in Physics Research A **429**, 88 (1999).

Ginzburg-Landau model and single-mode operation of a free-electron laser oscillator, C. S. Ng and A. Bhattacharjee, Physical Review Letters **82**, 2665 (1999).

INVITED TALKS BY PI IN INTERNATIONAL CONFERENCES

Ginzburg-Landau model for single-mode operation of a free-electron laser, 19th
International Free Electron Laser Conference, August 18-22, 1997, Beijing, China.

Ginzburg-Landau equation: a unified nonlinear model for high-gain amplifiers and low-gain
oscillators, 20th International Free Electron Laser Conference, August 16-21, 1998,
Williamsburg, Virginia.

INTERACTIONS/TRANSITIONS
None

NEW DISCOVERIES, INVENTIONS OR PATENT DISCLOSURES
None

HONORS
University of Iowa Faculty Scholar, 1997-2000
James Van Allen Natural Sciences Fellowship, 1996

Lifetime achievement honors prior to this effort : Fellow, American Physical Society, 1993